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DEPARTMENT OF THE NAVY
NAVAL APPLIED SCIENCE LABORATORY

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TECHNICAL REPORT

U. S. NAVAL APPLIED SCIENCE LABORATORY

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DEPARTMENT OF THE NAVY
BUREAU OF SHIPS

DEALUMINIZATION OF CAST ALUMINUM BRONZES

Lab. Project 930-76, Progress Report #2

SF 020-01-02, Task 0727

5 July 1967

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BROOKLYN, NEW YORK 11251

SUMMARY

Effects of microstructure, heat treatment and welding on the corrosion (dealuminization) resistance of cast aluminum bronzes (MIL-B-16033) after six months and one year exposure to flowing sea water are described. Results show that the bronzes are both composition and structure sensitive to corrosion attack. Heat treatment either eliminates or minimizes dealuminization attack; however, welding nullifies any advantages derived from heat treatment. Post-weld treatment can restore corrosion resistance provided proper filler materials are used.

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ADMINISTRATIVE INFORMATION

Ref: (a) NASL Program Summary SF 020-01-02, Task 0727 of 1 May 1967
(b) NASL Project 6355, Progress Report 1 of 25 Oct 1963
(c) NASL Project 6355, Tech Memo #1 of 17 Apr 1964
(d) NASL Project 6355, Tech Memo #2 of 20 Jan 1965
(e) NASL Project 6355, Tech Memo #3 of 26 May 1965
(f) NASL Project 6355, Tech Memo #4 of 3 Jun 1965
(g) NASL Project 6355, Tech Memo #5 of 8 Jul 1965
(h) Williams, W. L., Journal of the American Society of Naval Engineers, vol 69, p. 453 (Aug 1957)
(i) Schuseler, M. and Napolitan, D. S. Corrosion, vol 12, p. 25 (Mar 1956)
(j) Stead, D. D., Australasian Engineer, vol 44, p. 44 Mar 1951
(k) Cook, M., et. al., Journal of the Institute of Metals, vol 80, p. 419 (Apr 1952)
(l) Arnaud, D., et. al., Centre Technique Des Industries De La Fonderie Report (Aug 1964)
(m) Fed Test Method STD, No. 151a (May 1959)
(n) Mil Spec MIL-B-16033 (BUORD) (Feb 1951)

1. In connection with the U. S. Naval Applied Science Laboratory's (NASL) Program on Fabrication of Non-Ferrous Machinery Alloys, outlined in reference (a), the Laboratory is conducting an investigation on the deterioration of aluminum bronze casting alloys in sea water due to dealuminization attack, with particular emphasis on effects of heat treatment and welding on this corrosion phenomenon. Previous Laboratory studies* on dealuminization of cast aluminum bronze are described in references (b) through (g) which deal with the MIL-B-16033 alloys. The following report summarizes and analyzes the data of references (b) through (g) on the effects of heat treatment and welding on the dealuminization tendencies of the alloys after six months and one year exposure to flowing sea water.

Note: *Reported under Lab. Project 6355, which hereafter will be identified as Lab. Project 930-76.

ACKNOWLEDGMENT

2. The authors wish to express their gratitude and appreciation to Messrs. G. Sorkin and B. B. Rosenbaum of the Naval Ship Systems Command, and H. S. Sayre of the Naval Ship Engineering Center, for sponsoring and encouraging the program which served as the basis for this report. They are grateful for the assistance and guidance given by Mr. E. A. Imbembo, former Head, Metallurgy Branch of the U. S. Naval Applied Science Laboratory. Special acknowledgment is due to Mr. P. J. Frintzilas for his assistance in the metallographic studies.

INTRODUCTION

3. The phenomenon of "Dealuminization" has been observed in certain cast aluminum-bronze alloys, which have been subjected to salt water environments for prolonged periods (reference (h)). This attack is considered to be electrochemical in nature and results in the leaching out of aluminum, leaving behind a low strength, friable copper material. The insidious nature of this corrosive attack manifests itself by a deterioration of the internal structure, not always detected by mere visual inspection. The dealuminized area, once detected, can be recognized macroscopically by the presence of the characteristic deep copper color and, depending on the microstructure, can occur as a "layer-like" peripheral attack or one which is random and "spotty" in nature.

4. The property affected by this type corrosion and sensitive enough to detect meaningful differences, is the ultimate tensile strength. Percent elongation is too sensitive to surface imperfections and other types of discontinuities, and therefore is not considered a useful parameter for study. On the other hand, yield strength does not significantly change with varitions in amount of dealuminized areas.

5. Classically, dealuminization is attributed to the difference in electrochemical characteristics between the copper-rich alpha and aluminum-rich gamma-2 phases (reference (1)). In the presence of sea water, an electrolytic cell is set up at the interface of the alpha and gamma-2 phases. The latter, being less noble than the alpha phase, will preferentially corrode, accompanied by a severe loss in aluminum. If the anodic constituent is present in the microstructure as an interconnected secondary phase, it will provide an easy path for dealuminization to follow. It has been observed that in some cases, the rate of attack diminishes as the penetration increases. This phenomenon may be attributed to the inability of the electrolyte to easily make intimate contact with the anodic and cathodic areas.

6. To date, it appears that there are two practical means of combatting dealuminization and they are as follows:

a. Modification of Composition

b. Heat Treatment

7. Additions of iron and nickel to the basic copper-aluminum alloy system have been effective in reducing or eliminating the amount of gamma-2 produced, thereby improving the resistance to dealuminization. Iron acts as a grain refiner (reference (j)) but more significantly, it forms an iron-rich phase in combination with Al which appears as small globules and/or rosettes in the microstructure. In this manner, the addition of iron reduces the amount of aluminum available to form gamma-2.

8. Similarly, nickel (in amounts greater than 2%) combines with aluminum in the Cu-Al solid solution to form a new "kappa" phase believed to be NiAl (reference (k)). This phase takes the form of elongated rods, often in a lamellar array with alpha. Thus, it has been reported that nickel improves dealuminization resistance by forming a "pearlitic" boundary layer between the aluminum rich and copper-rich phases (reference (l)). In addition, the formation of nickel-rich kappa reduces the amount of Al available to form gamma-2 and results in an apparent shift of the alpha/alpha plus gamma-2 phase boundary to higher Al contents.

OBJECTIVE

9. The objective of this work was to determine the effects of heat treatment and welding on the dealuminization tendencies of aluminum bronze casting alloys conforming to MIL-B-16033 (Classes 1 through 4).

PROCEDURE

10. Material. The following casting alloys were utilized in this investigation:

Mil Spec MIL-B-16033	Remarks*
Class 1	Non-Heat Treatable Alloy 4% Fe; 9% Al
Class 2	Heat-Treatable Alloy 1% Fe; 10% Al
Class 3	Heat-Treatable Alloy 3% Fe; 10% Al; 0.4% Mn; 1% Ni
Class 4	Heat-Treatable Alloy 4% Fe; 10% Al; 2% Mn; 5% Ni

Note: *Nominal percentages for alloys studied.

11. Founding. The foundry techniques employed to produce the test plate castings were:

a. Gating - Due to the dross forming tendencies of aluminum bronze alloys, a gating and risering system, illustrated in Figure 1, was developed by NASL in order to minimize the pickup of gas from the mold and dross in the test casting.

b. Melting and Casting - Charges consisted of approximately 2200 lbs. (remelt and commercial ingot) melted in a 2400 lb capacity oil-fired furnace. Deoxidation was accomplished by plunging magnesium rod (2 oz/100 lbs) directly into the ladle prior to pouring. Tapping temperature was approximately 2200°F and castings were poured at approximately 2180°F into molds rammed in green sand which were skin dried. All test material was cast in the same manner and eighty plate castings, 2-1/4" x 11" x 1/2" thick were produced from a single heat of each alloy. A total of 320 plates were cast for this work.

12. Welding. The metal-inert-gas consumable electrode process was used in the fabrication of the welded test specimens. Welding was accomplished manually in the flat position, employing D. C. reverse polarity and argon as the shielding gas. A preheat and interpass temperature of approximately 300°F was maintained with average power settings of approximately 24 volts and 300 amperes. The filler wire was 5/64" in diameter and was fed at a wire speed of approximately 16 ft./min. Commercial filler wires, Code 3 (89 Cu-10 Al-1 Fe)

and Code 4 (82 Cu-10 Al-4 Ni-4 Fe) were used in fabrication of welded test specimens. The filler wires are identified on a deletable page at the end of the report. It should be noted that the welding conditions mentioned above represent average values and depending on the alloy under consideration, slight adjustments were made in the welding settings.

13. A single-vee butt joint, having a 60° included angle (Figure 2), was the design used for the welded test specimens. The joints were machine beveled and ground. Prior to welding, the joints were buffed and thoroughly cleaned with a suitable solvent. Stringer bead technique was used and each weld layer was wire brushed and inspected for defects which were removed by grinding.

14. Both halves of the weld assembly were inclined 3° from the horizontal and restrained to compensate for the pull back resulting from contraction of the weld metal upon solidification. In this manner, relatively flat weldments were obtained from which transverse-weld tensile specimens were machined.

15. Testing. The following tests were used in this investigation:

a. Nondestructive Testing - All cast test plates were examined by X-ray to ascertain their soundness. In addition, machined test bars and transverse-weld test specimens were so examined, and only those which were found to be relatively sound and free of gross defects were used in the corrosion studies.

b. Chemical Analyses - Chemical analysis (Table 1) was performed on each heat, in order to establish the composition of the base material and compliance with the appropriate specification requirements. In addition, as-deposited weld metal chemistry for each weld combination, i.e., alloy type and filler wire, was determined

c. Tensile Specimens - Each plate casting provided sufficient material for two flat-type tension specimens, shown in Figure 3. In the case of the transverse weld specimens, these were machined after preparation and welding of the test plate castings. Tensile tests for all conditions were conducted in accordance with references (m) and (n).

d. Heat Treatment - The heat treatments used in this investigation (Tables 2 and 3) were applied to test plate castings prior to machining. Hereafter, the term "heat treatment" designates the following: 1625°F (2 hr) WQ; 1125°F (1-1/2 hr) WQ, unless otherwise stated. A post-weld thermal treatment was applied only to welded specimens whose base metal received this treatment.

e. Metallography - Metallographic examination was performed on specimens taken from the shank ends of the tensile bars before testing or from the gage section of the transverse-weld test specimens after fracture. These specimens were rough polished by conventional techniques and final polished in a Syntron vibrating polisher, using a 30 minute cycle with Shamva (MgO) in a vehicle of glycerine and ethylene glycol. Specimens were etched in an aqueous solution of ammonium persulfate for approximately 7-15 seconds and studied at appropriate magnifications.

f. Corrosion - The U. S. Marine Engineering Laboratory (MEL) directed the exposure tests for two periods, six months and one year. One half of the total specimens for each alloy was retained by NASL as controls and the balance was forwarded to MEL for corrosion testing in flowing sea water (3 ft./sec.) at the Harbor Island Corrosion Test Station, Wrightsville Beach, North Carolina. Of this group, one half was exposed for six months and the remainder for one year. The position of the test specimens, relative to the sea water flow, is shown in Figure 4. After the prescribed exposure period, specimens were removed, photographed, cleaned and returned to NASL for further evaluation. Tension tests were conducted on exposed specimens to determine the effect of corrosion (dealuminization) on the tensile properties. In addition, metallographic studies were made on selected specimens in order to determine the nature and extent of the dealuminization attack.

RESULTS AND DISCUSSION

MICROSTRUCTURES OF BASE METAL

16. Class 1 (9% Al; 4% Fe). The chemical composition (Table 1) of Class 1 bronze is designed to yield a single phase alloy, free from the dealuminization prone alpha plus gamma-2 eutectoid. However, the addition of 4 percent iron to the Cu-Al binary results in the formation of a new microstructural phase which takes the form of large rosettes and/or finely dispersed particles. The new phase, referred to as iron-rich kappa, often takes on a "cored" appearance when etched with 10% ammonium persulfate solution, indicative of chemical composition gradients. The authors believe this phase to be a body-centered cubic alpha iron with a wide range of compositions (pure Fe to Fe containing Al). This phase is illustrated in the microstructures of the Class 1 alloy presented in Figure 5, as rosettes and finely dispersed particles.

17. Cast materials are characterized by relatively inhomogenous structures which may be attributed to non-equilibrium cooling. Thus, the as-cast microstructure of Class 1 bronze (Figure 5a) contains a great deal of secondary phase other than the Fe-rich kappa mentioned above. It is felt that the phase encountered is beta, dragged down from higher temperatures as a

result of non-uniform cooling of the casting. Beta is an aluminum-rich phase which may undergo a martensitic transformation when rapidly cooled from temperatures at which it is stable. Its presence in the microstructure increases the possibility of a selective phase corrosion (dealuminization) attack on the as-cast material.

18. Application of an 1125°F tempering treatment reduces the amount of beta phase, as observed in Figure 5b. Reduction in the amount of secondary phase at proeutectoid temperatures indicates that the tempering is performed in a one phase alpha field and substantiates the fact that the eutectoid is not encountered in the as-cast or slow cooled structures of the Class 1 bronze studied herein. Insufficient time at temperature accounts for the small isolated areas of beta encountered in the 1125°F microstructure.

19. In an attempt to maximize strength and corrosion resistance, the classical two step aluminum bronze "heat treatment" was applied to the Class 1 alloy. Solution annealing at 1625°F, results in an alpha-beta microstructure. The beta is martensitic and characterized by needle-like platelets of alpha. Upon tempering at 1125°F, the needles act as nuclei for alpha growth and the amount of beta is diminished. The microstructure of this condition is presented in Figure 5c and reveals a eutectoid-like pattern of residual beta in alpha.

20. Class 2 (10% Al; 1% Fe). To improve the strength properties of aluminum bronze over those exhibited by Class 1, the aluminum content is increased to approximately 10 percent. Class 2 bronze undergoes the alpha plus gamma-2 eutectoid transformation upon slow cooling through the 1100-1000°F temperature range, and becomes susceptible to selective phase corrosion attack. The as-cast microstructure, illustrated in Figure 6a, contains a continuous network of martensitic beta and eutectoid in a matrix of primary proeutectoid alpha. The presence of martensitic beta and only a limited amount of eutectoid indicates that the cast material cooled rapidly through the eutectoid isotherm.

21. Tempering this alloy at 1125°F increases the amount of beta phase (martensitic) and consequently reduces the amount of alpha compared to the as-cast structure. Figure 6b reveals that the eutectoid has been eliminated, indicating that 1125°F tempering temperature is well above the eutectoid isotherm in this alloy. This treatment has altered the anodic-cathodic ratio which plays a significant role in the electrochemical dealuminization corrosion attack. By reducing the amount of cathodic alpha phase, the current driving the corrosion process, as well as the number of sites at which the reaction may be initiated, are reduced and the overall extent of corrosion encountered should be less than in the as-cast condition.

22. The full "heat treatment" is especially applicable to the Class 2 type aluminum bronze. By quenching from above the eutectoid temperature, the undesirable microstructural constituent (alpha plus gamma-2) is eliminated. At 1625°F, the alloy is in an approximately all beta phase field; rapid cooling results in the martensitic transformation which is characterized by the formation of fine alpha needles in a Widmanstatten array. Subsequent tempering at 1125°F (an alpha-beta phase field) results in a coarsening of growth of alpha needles. Figure 6c illustrates the fully "heat treated" microstructure, which consists of acicular alpha in a beta matrix. The discontinuity of the beta, caused by the Widmanstatten pattern of alpha, provides a material capable of improved selective phase corrosion resistance.

23. Class 3 (10% Al; 3% Fe; 1% Ni). To improve the sea water corrosion resistance of aluminum bronze, nickel and iron additions are made to the binary Cu-Al system. The relatively high aluminum content (10.0%) of the Class 3 alloy results in the formation of eutectoid constituents in the "as-cast" material. Thus, nickel is added to shift the alpha/alpha plus gamma-2 solvus line to higher aluminum contents. (Less than 2.0% Ni is relatively ineffective).

24. At the level of Ni added to the Class 3 bronze, the above mentioned shift is slight and the eutectoid constituent is encountered in the "as-cast" condition. Figure 7a is typical of the as-cast microstructure studied and consists of alpha grains in a beta matrix. The rosettes of Fe-rich kappa are evidenced in the structures of this bronze. The beta is not martensitic (needle-like) but appears to be in transition. At 250X magnification, areas along the alpha-beta interfaces appear darkened and are considered to be in the process of transforming to alpha + gamma-2. This structure is indicative of rapid cooling through the beta transformation temperature.

25. Tempering the "as-cast" structure at 1125°F (Figure 7b) causes the beta phase to undergo a martensitic transformation. On the other hand, "heat treatment" of Class 3 bronze results in a microstructure (Figure 7c) equivalent to that of the Class 2 discussed above (Figure 6c).

26. Class 4 (10% Al; 4% Fe; 5% Ni). Before analyzing the microstructures encountered in the Class 4 aluminum bronze, a brief discussion of the effects of nickel in amounts greater than 2% is offered. Nickel combines with the aluminum in the Cu-Al solid solution to form a compound, kappa, which is believed to be a nickel-aluminum with an ordered body-centered cubic structure (similar to CsCl). This phase appears as elongated rods in a lamellar array with alpha. Metallographic analysis reveals that lamellar kappa (nickel-aluminum) is nucleated primarily at alpha-beta grain boundaries, and grows at the expense of beta in a direction coincident with alpha grain growth.

27. The ability of nickel to tie up aluminum in the form of kappa phase results in the apparent shift of the alpha/alpha plus gamma-2 phase boundary to higher aluminum contents. Increased amounts of aluminum may be tolerated before the eutectoid is encountered. Thus an alloy with sufficient nickel will not cross the eutectoid isotherm and heat treatment will control the size, shape and distribution of the alpha, beta and Ni-rich kappa phases discussed previously.

28. The as-cast microstructure consists of an acicular array of alpha grains which are marked by lamellar rods of Ni-rich kappa phase (pearlitic in appearance). Examination of the structure presented in Figure 8a reveals several dark-etching areas in the midst of the alpha. At high magnification, it has been observed that these regions are abundant in Ni-rich kappa and beta. The random occurrence of areas rich in beta and kappa provide microstructural inhomogeneities which may lead to severe localized corrosion, manifesting itself as a pitting and/or dealuminization attack.

29. The conventional "heat treatment" was applied to homogenize the structure and eliminate the areas with high concentration of beta and kappa phases. Quenching Class 4 bronze from 1625°F produces a fine martensitic structure free from primary-proeutectoid alpha. Subsequent tempering at 1125°F transforms the beta to alpha plus kappa. The resultant microstructure is shown in Figure 8b.

EFFECTS OF CORROSION EXPOSURE (UNWELDED)

30. The tensile properties of the control and exposed base metal specimens are tabulated in Table 2. Tensile strength is represented graphically as a function of exposure time in Figures 9 through 12. Examination of these shows two trends: (a) as-cast tensile strength is decreased after sea water exposure and (b) thermal treatment improves sea water corrosion resistance over that of the as-cast condition.

31. With regard to the as-cast material, the most pronounced losses in strength were displayed by the Class 2 and Class 3 bronzes (Figures 10 and 11) both of which contain the gamma-2 phase in a eutectoidal distribution in their microstructures. In addition to the alpha plus gamma-2 eutectoid, these alloys contain continuous networks of Al-rich beta phase which undergo dealuminization, as illustrated in Figure 13. Class 1 and 4 bronzes (Figures 9 and 12) are not prone to the continuous secondary phases and thus exhibit better as-cast corrosion resistance. However, these alloys are not impervious to losses in strength and do suffer from localized corrosion attack (pitting-type) which ultimately results in plugs of dealuminization.

32. Full "heat treatment" improved control strength properties of the heat treatable alloys, and resulted in freedom from dealuminization and its associated losses in strength. The improved dealuminization resistance of the Class 2 and 3 alloys is due to a redistribution of the microstructural constituents and the elimination of the continuous Al-rich phase. In the case of the Class 4 alloy, improved corrosion resistance is attributed to elimination of localized concentrations of Al-rich phases. Thus, it is shown that dealuminization corrosion is structure sensitive.

33. An 1125°F tempering treatment was applied to the Class 1, 2 and 3 bronzes. The data in Table 2 show that this treatment improved the exposed tensile properties over those of the as-cast condition (see Figures 9, 10 and 11). However, Class 2 and 3 alloys still remain susceptible to dealuminizaion. Since Class 1 (9.0% Al) was tempered in a single phase alpha field (1125°F), residual beta was transformed to alpha resulting in a structure more resistant to dealuminization. Tempering the Class 2 and 3 alloys (10.0% Al) at 1125°F merely eliminates the eutectoid constituent and replaces it with beta (martensitic) which results in a reduced rate of dealuminization attack.

EFFECTS OF CORROSION EXPOSURE (WELDED)

34. Pertinent data concerned with fabrication of the welded specimens have been outlined above. Results of sea water corrosion on the tensile properties of weldments are presented in Table 3. The effects of welding and post-weld treatment on the tensile properties (transverse-weld) are shown in Figures 9 through 12, as a function of exposure time.

35. All welded control specimens (Table 3) exhibited base metal failures, except Class 4 specimens which failed in the weld deposit proper. Sea water exposure resulted in: (a) significant reductions in joint tensile properties and (b) shifts in fracture location, i.e., base metal to HAZ and/or weld.

36. The losses in tensile strength encountered with the welded specimens are illustrated in Figures 9 through 12 and are attributed to dealuminization corrosion attack. As-welded Class 1 (Figure 9), regardless of the condition of the base metal, was subject to dealuminization attack in the Code 3 weld deposit. It should be noted that post-weld heat treatments did not entirely eliminate dealuminization in the weld metal, but by decreasing the rate of attack in this region, resulted in improved joint strength.

37. Classes 2 and 3 (as-cast, as-welded) weldments, in contrast to the Class 1 alloy above, exhibited base metal tensile fractures, far removed from the HAZ and weld areas. Though all weldments were fabricated with Code 3 filler wire (susceptible to dealuminization) the as-cast base metal was more prone to severe attack than the weld deposit. On the other hand, when these alloys are fully "heat treated" (prior to welding), tensile failures shift to the weld zone. This trend illustrates the structure sensitivity of the dealuminization phenomenon. Post-weld thermal treatments (Figures 10 and 11) improved the exposed tensile joint strength compared to the as-welded material. However, there was still some evidence of dealuminization in the Code 3 weld deposit and HAZ.

38. Class 4 control specimens (in all conditions), welded with Codes 3 and 4 filler wires, displayed weld metal failures (see Table 3). In the as-cast and welded condition, specimens fabricated with Code 3 wire were subject to dealuminization in the weld and heat-affected zones. The beneficial effects of the 1125°F post-welded treatment are reflected by (a) a shift of tensile fracture from HAZ (as-welded) to weld deposit and (b) improved dealuminization resistance, as evidenced by exposed joint properties.

39. Class 4 bronze, welded with a matching composition filler wire (Code 4), suffered from severe dealuminization in the as-welded HAZ due to the formation of excessive beta phase. Figure 14 (left) shows the beta structure in the HAZ, indicative of rapid cooling from elevated temperature. The application of an 1125°F post-weld treatment resulted in an HAZ structure essentially equivalent to the base metal (Figure 14, right), i.e., similar to the fully "heat-treated" condition.

40. A critical problem to producers of aluminum and nickel-aluminum bronze castings for sea water applications is that of weld repair. As has been pointed out, the welding process tends to reduce the corrosion resistance of aluminum and nickel-aluminum bronze weldments. For example, the Class 1 alloy reported herein displayed adequate corrosion resistance in the unwelded condition. However, the use of Code 3 filler wire resulted in weldments subject to severe localized corrosion attack with accompanying losses in joint tensile Properties. Code 3 filler wire has a significantly higher Al content than that of the Class 1 alloy (9.9% Al vs. 9.0% Al). Thus, in an electrically isolated assembly, the weld deposit and adjacent HAZ are preferentially attacked. A similar situation is encountered in the Class 4 material fabricated with a non-matching composition filler (Code 3). These examples serve to illustrate the importance of matching the chemical composition of the filler wire to that of the alloy being welded.

41. Chemical composition is not the only factor governing the performance of aluminum bronze weldments in flowing sea water. The microstructure of the base plate relative to that of the weld deposit also determines the region of the weldment which will be most susceptible to dealuminization. This is verified by the fact that as-cast Class 2 and 3 bronzes welded with Code 3 filler wire suffered significant losses in exposed tensile strength with specimen failure occurring in the base metal. Since the Class 2 and 3 alloys have approximately the same aluminum content (10%) as the filler wire, these failures are attributed to microstructural differences between the as-cast base plate and the weld deposit. On the other hand, when Class 2 and 3 materials were "heat treated" prior to welding, their corrosion susceptibility was altered, resulting in weld zone failures. Thus, it can be seen that microstructure is an important consideration where corrosion (dealuminization) is concerned.

42. Since relative chemical composition and microstructure of the weld deposit and base metal appear to play such an important role in the corrosion behavior of weldments, it appears that close matching of materials on the basis of strength and composition is essential. Insofar as microstructural differences are concerned, the current trend is towards post-weld tempering treatments in an attempt to homogenize the overall structure of the weldment and thus improve resistance to selective corrosion attack.

CONCLUSIONS

43. Based on the results of tests conducted in this investigation, the following conclusions are drawn concerning the MIL-B-16033 aluminum bronze alloys:

a. "As-cast" Class 1 bronze displays adequate resistance to dealuminization by retaining a large portion of its control strength properties after one year exposure in sea water.

b. Multi-phase Al and Ni-Al bronzes (Class 2 and 3) are subject to rapid dealuminization and significant losses in strength when exposed to flowing sea water in the "as-cast" condition.

c. "Heat treatment" (1625°F (2 hr) W.Q. - 1125°F (1-1/2 hr)WQ.) of MIL-B-16033 bronzes improves both strength and corrosion resistance.

d. Alloy additions of nickel and iron to aluminum bronze (Class 4) improve "as-cast" strength and dealuminization resistance over that of alloys lean in nickel and iron (Class 2 and 3).

e. In general, the bronzes are both composition and structure sensitive relative to dealuminization corrosion attack.

f. Welding on "as-cast" or previously heat treated bronzes results in accelerated corrosion (dealuminization) attack.

g. Application of an 1125°F (1-1/2 hr) W.Q. post-weld thermal treatment results in improved exposed tensile joint strength, compared to the "as-welded" material.

h. "As-deposited" Code 3 filler wire is susceptible to dealuminization attack.

i. Code 4 (Ni-Al bronze) filler wire is also subject to dealuminization attack in the "as-deposited" condition, but responds favorably to post-weld treatment at 1125°F.

FUTURE WORK

44. Results of six month and one year sea water corrosion tests on cast manganese aluminum bronze (MIL-B-21230A - Alloy 2) with and without alloying additions of tin, are currently being evaluated. A report will be forwarded by July 1967.

45. NASL has recently completed six month corrosion tests on several nickel-aluminum bronze alloys with modified iron-to-nickel ratios. In addition, the 1300°F heat treatment recommended by NASL and subsequently prescribed in MIL-B-23921 - Amendment 2 was applied to these alloys prior to sea water exposure. Results will be reported by August 1967.

46. Additional heats of aluminum bronze castings with varying compositions (Al, Ni and Fe) are being manufactured. Results of six months sea water exposure tests performed on cast and welded specimens will be reported by June 1968.

IDENTIFICATION OF PROPRIETARY PRODUCTS

Code 3 Filler Wire - Ampcotrode 10

Code 4 Filler Wire - Duratrode

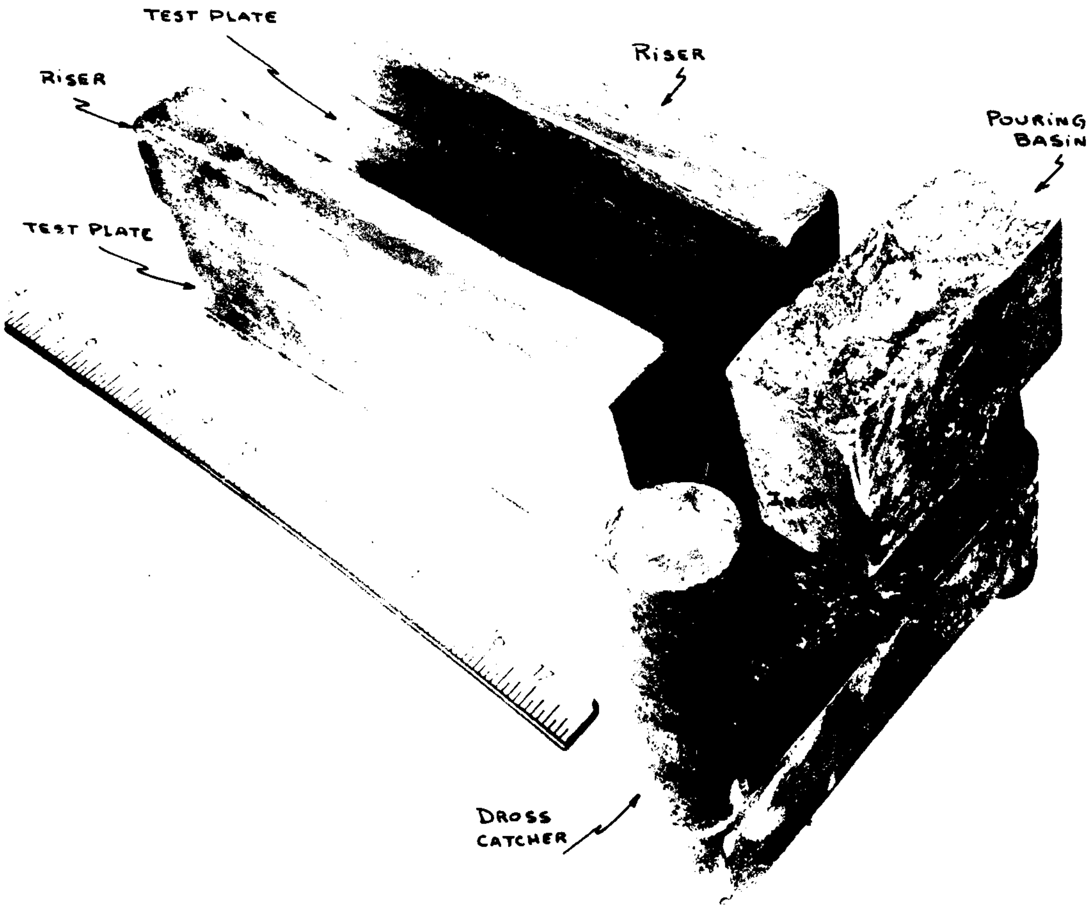


FIG. 1 ALUMINUM BRONZE TEST PLATE CASTING ARRANGEMENT

U.S. NAVAL APPLIED SCIENCE LABORATORY
Photo L-29017-1

Lab. Project 930-76
Progress Report 2

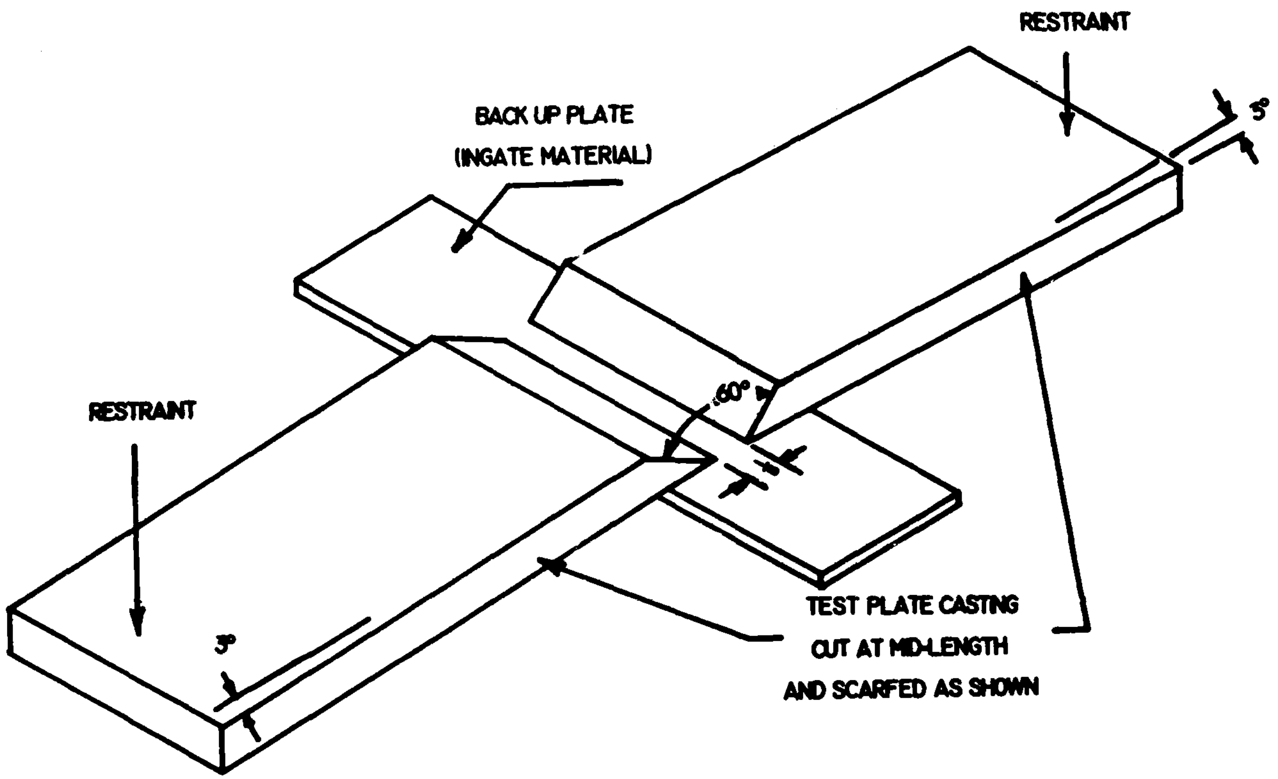
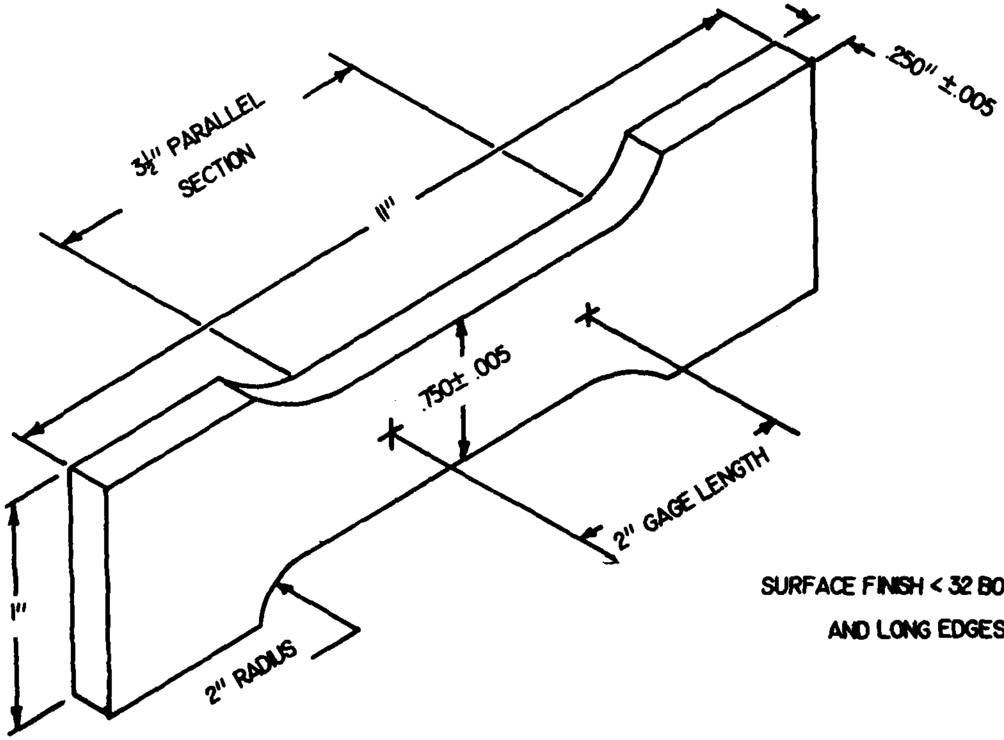


FIG. 2 TEST PLATE WELD ASSEMBLY

U.S. NAVAL APPLIED SCIENCE LABORATORY
Photo L-20017-2

Lab. Project 930-75
Progress Report 2



SURFACE FINISH < 32 BOTH SIDES AND LONG EDGES.

FIG. 3 TENSILE SPECIMEN FOR CORROSION STUDY

U.S. NAVAL APPLIED SCIENCE LABORATORY
Photo L-20017-3

Lab. Project 930-76
Progress Report 2

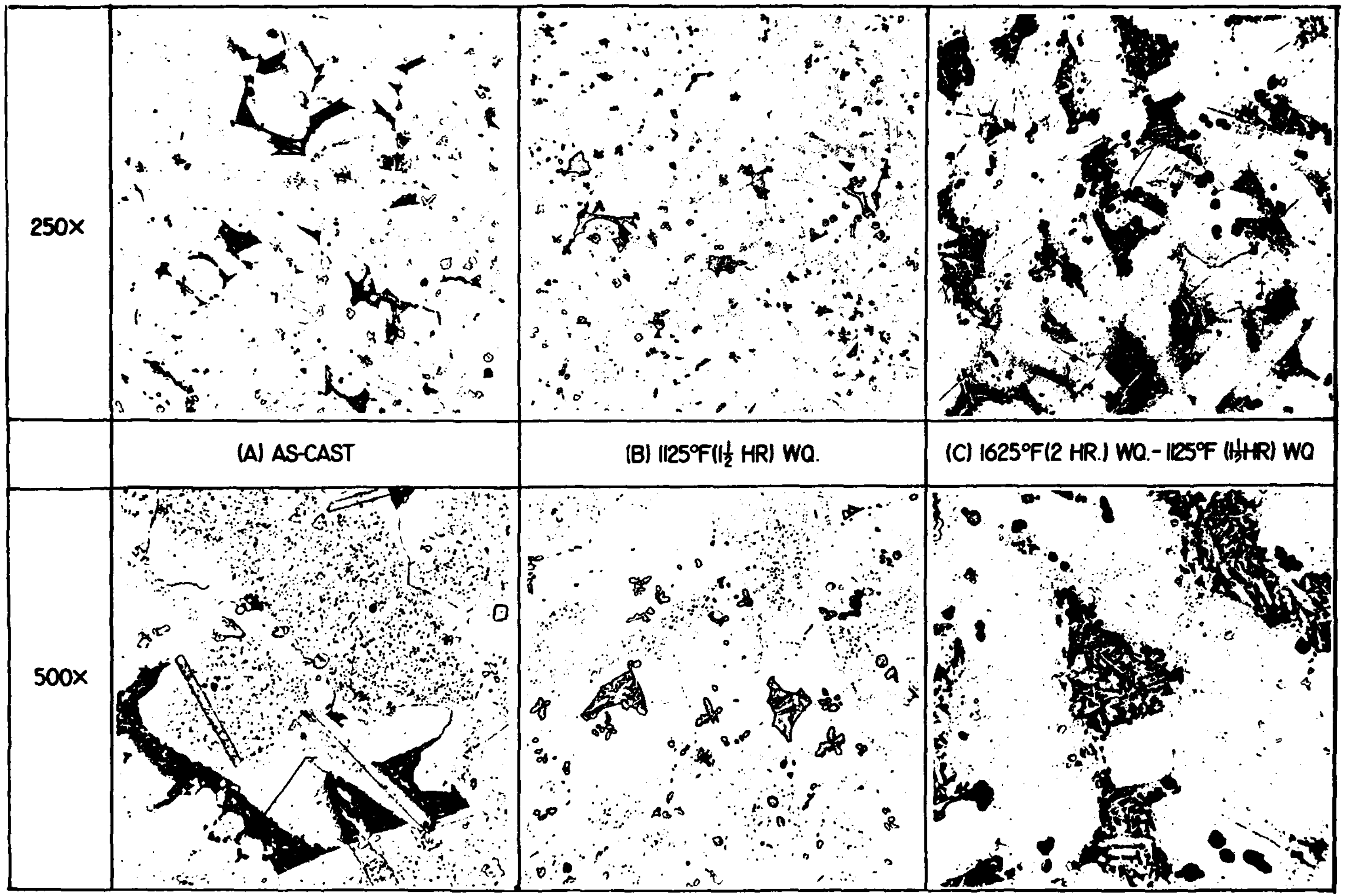


FIG. 5 STRUCTURE OF CLASS I BRONZE (9% AL-4%FE) PRIOR TO SEA WATER EXPOSURE

U.S. NAVAL APPLIED SCIENCE LABORATORY
Photo L-20017-5

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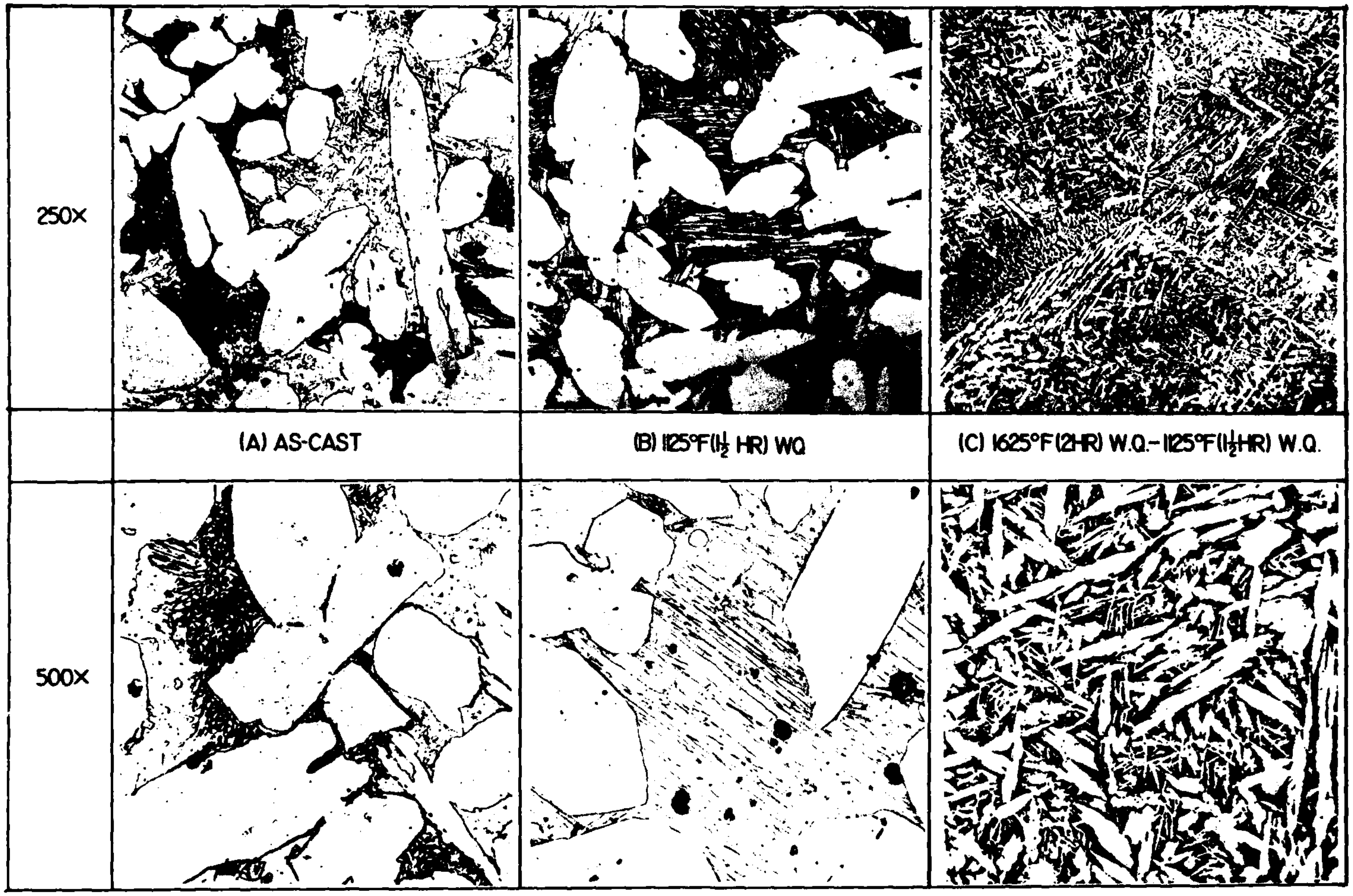

FIG. 6 STRUCTURES OF CLASS 2 BRONZE(10% AL-1% FE) PRIOR TO SEA WATER EXPOSURE.

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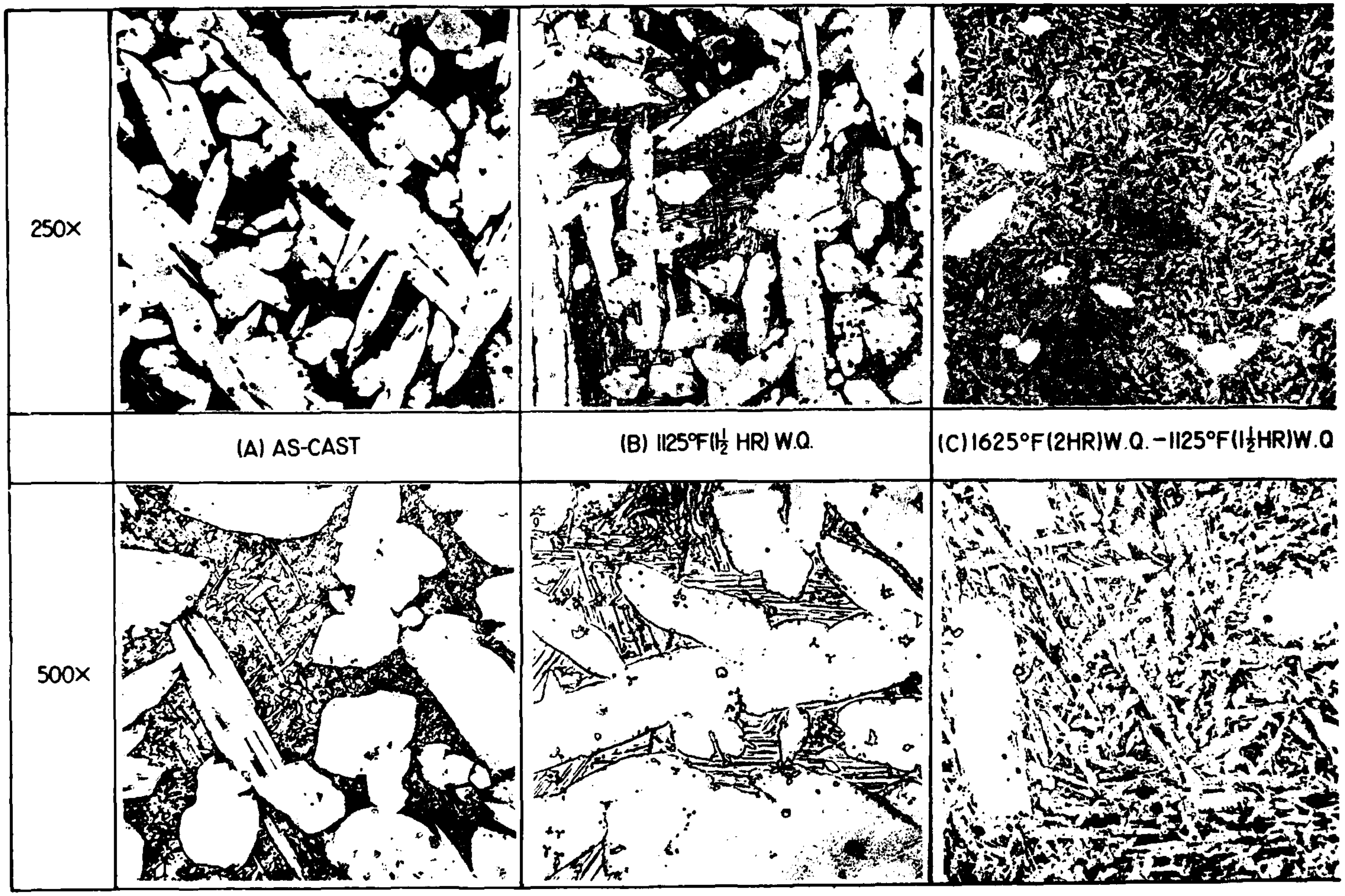

FIG. 7 STRUCTURES OF CLASS 3 BRONZE (10% AL-3%FE-1%NI) PRIOR TO SEA WATER EXPOSURE

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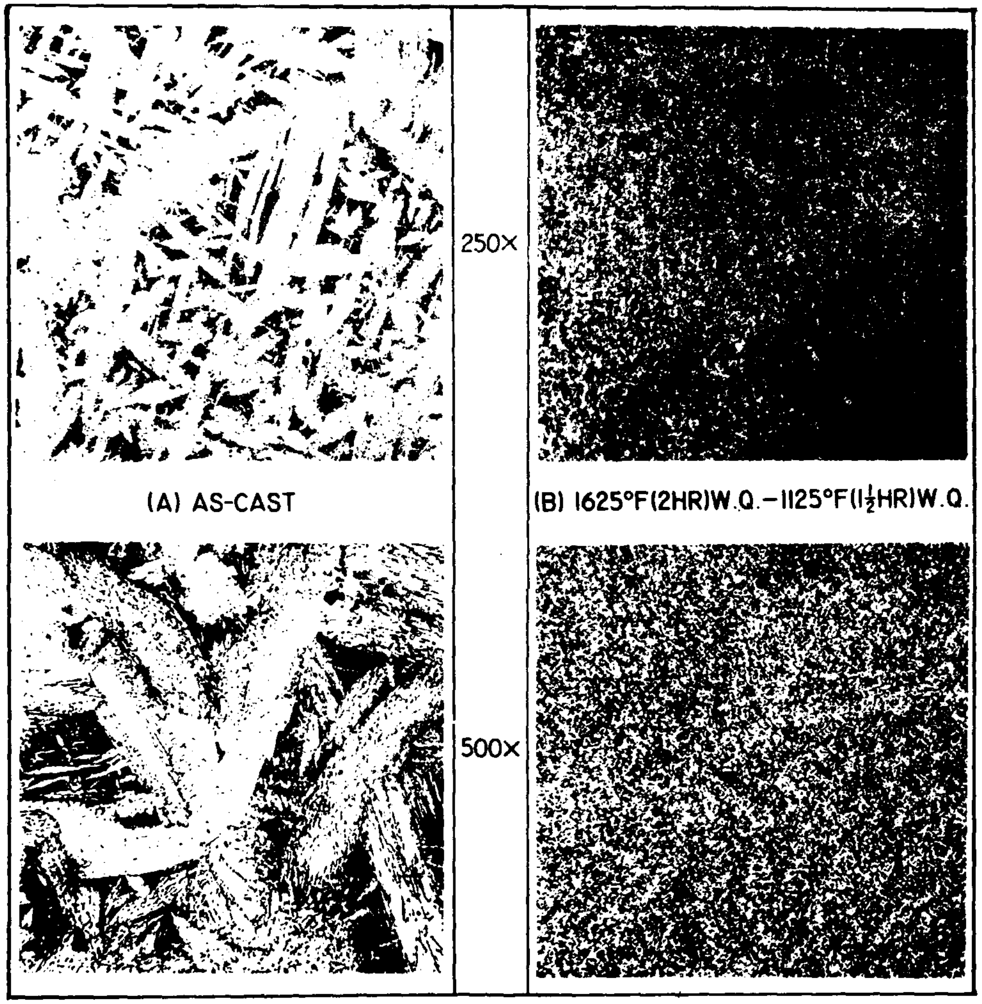

FIG. 8 STRUCTURES OF CLASS 4 BRONZE(10%AL 4%FE 5%NI) PRIOR TO SEA WATER EXPOSURE

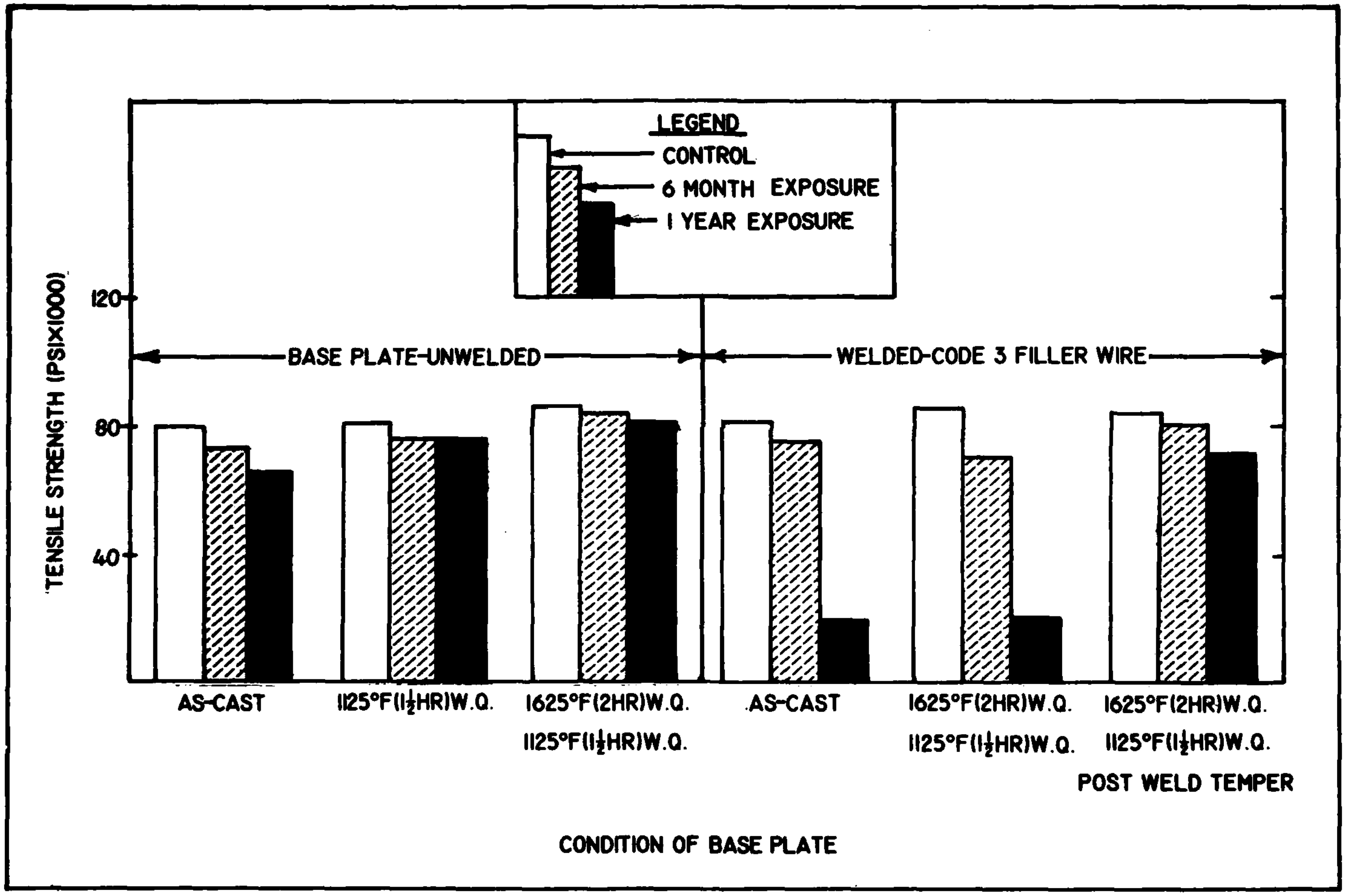

FIG. 9 EFFECT OF SEA WATER EXPOSURE ON CLASS I ALUMINUM BRONZE MIL-B-16033

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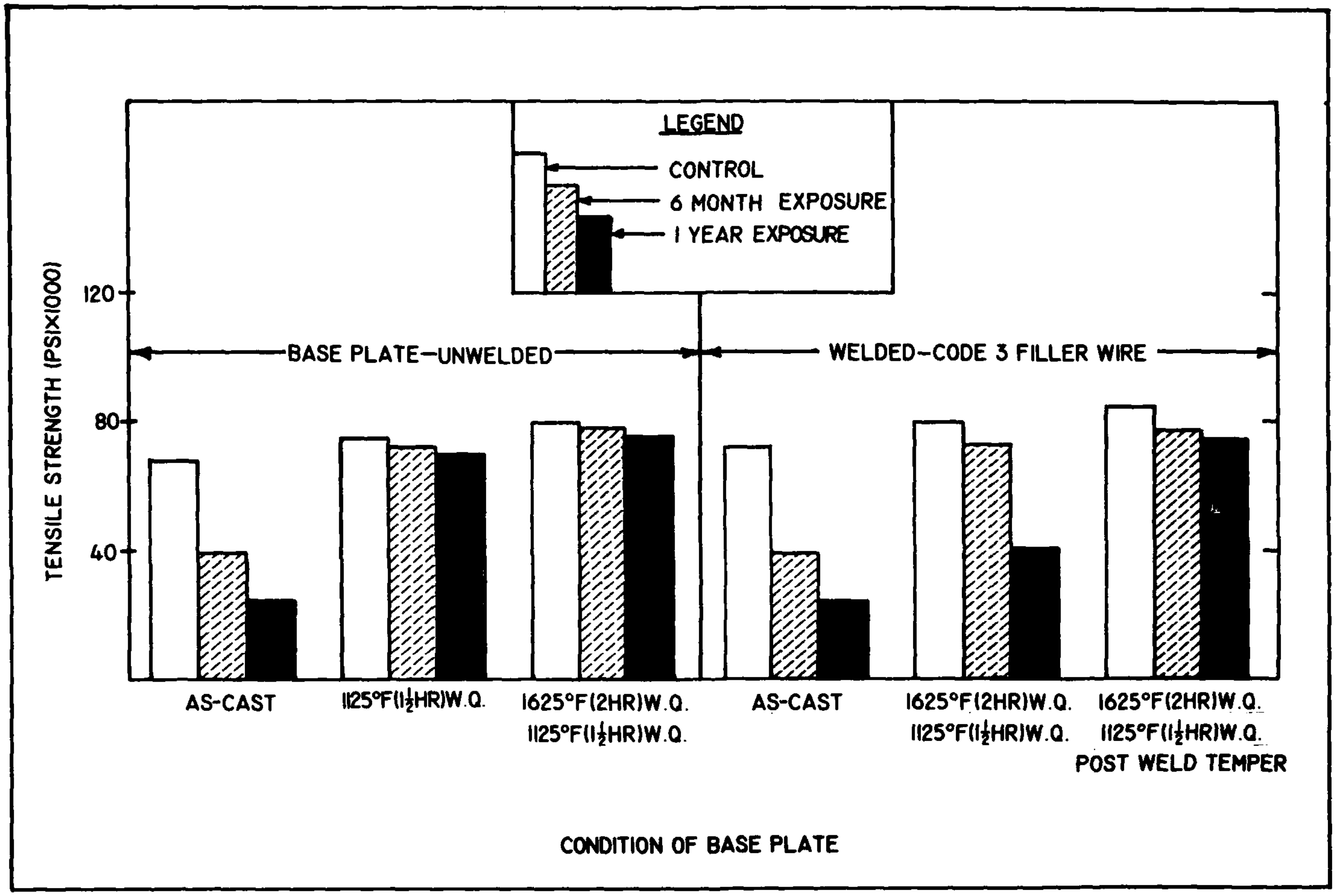

FIG. 10 EFFECT OF SEA WATER EXPOSURE ON CLASS 2 ALUMINUM BRONZE MIL-B-16033

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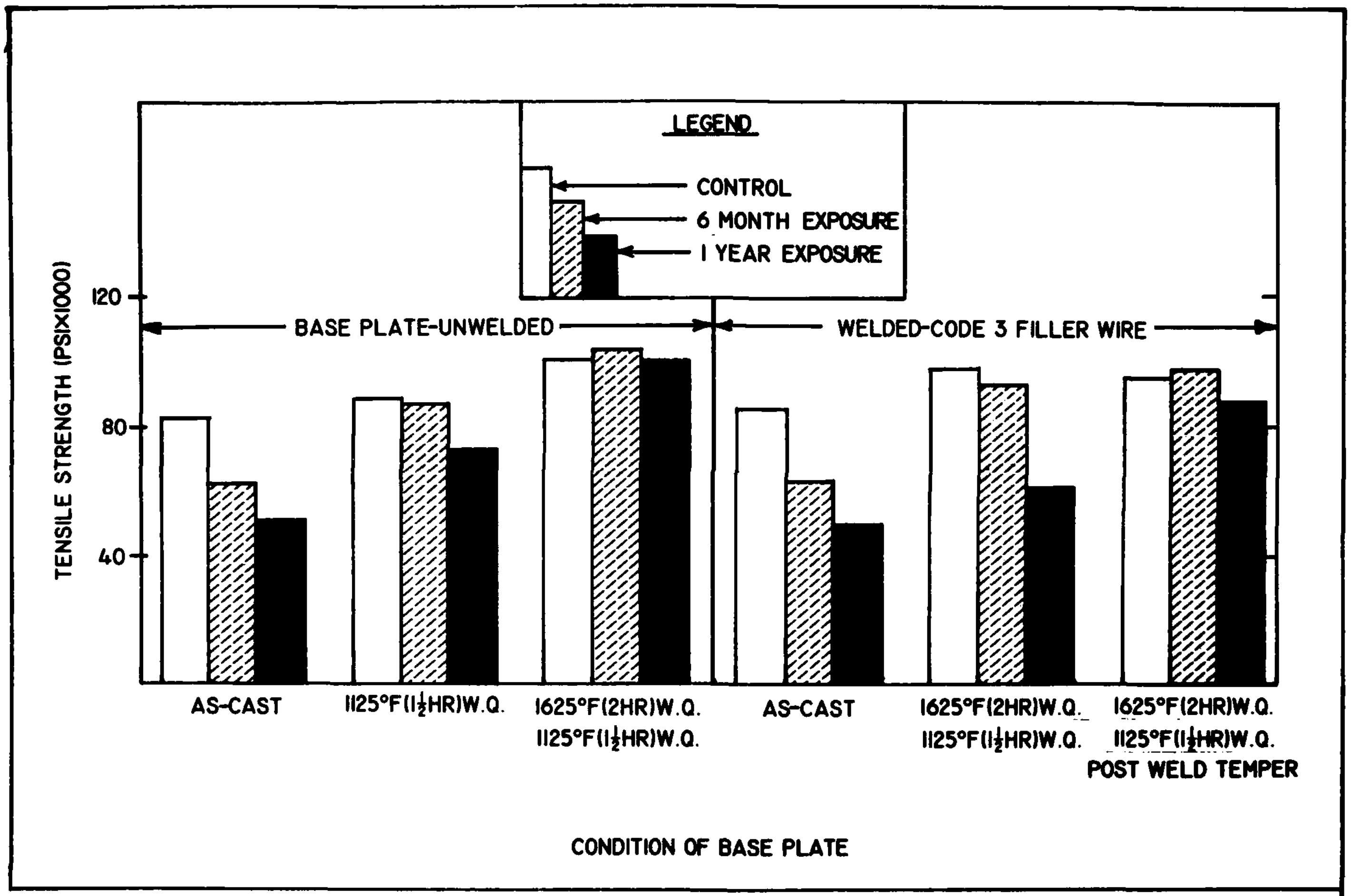

FIG. 11 EFFECT OF SEA WATER EXPOSURE ON CEASS 3 ALUMINUM BRONZE MIL-B-16033

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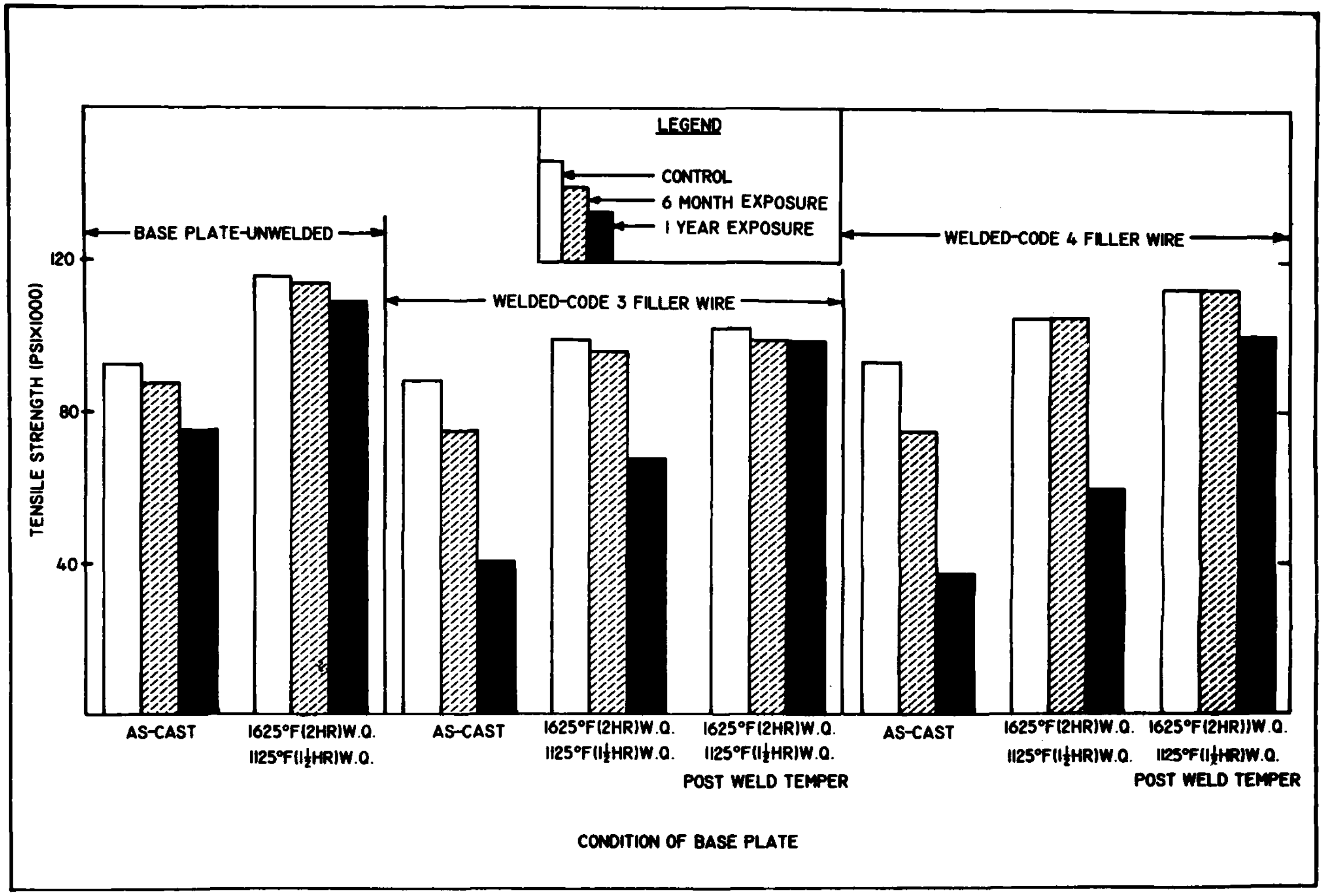

FIG. 12 EFFECT OF SEA WATER EXPOSURE ON CLASS 4 ALUMINUM BRONZE MIL-B-16033

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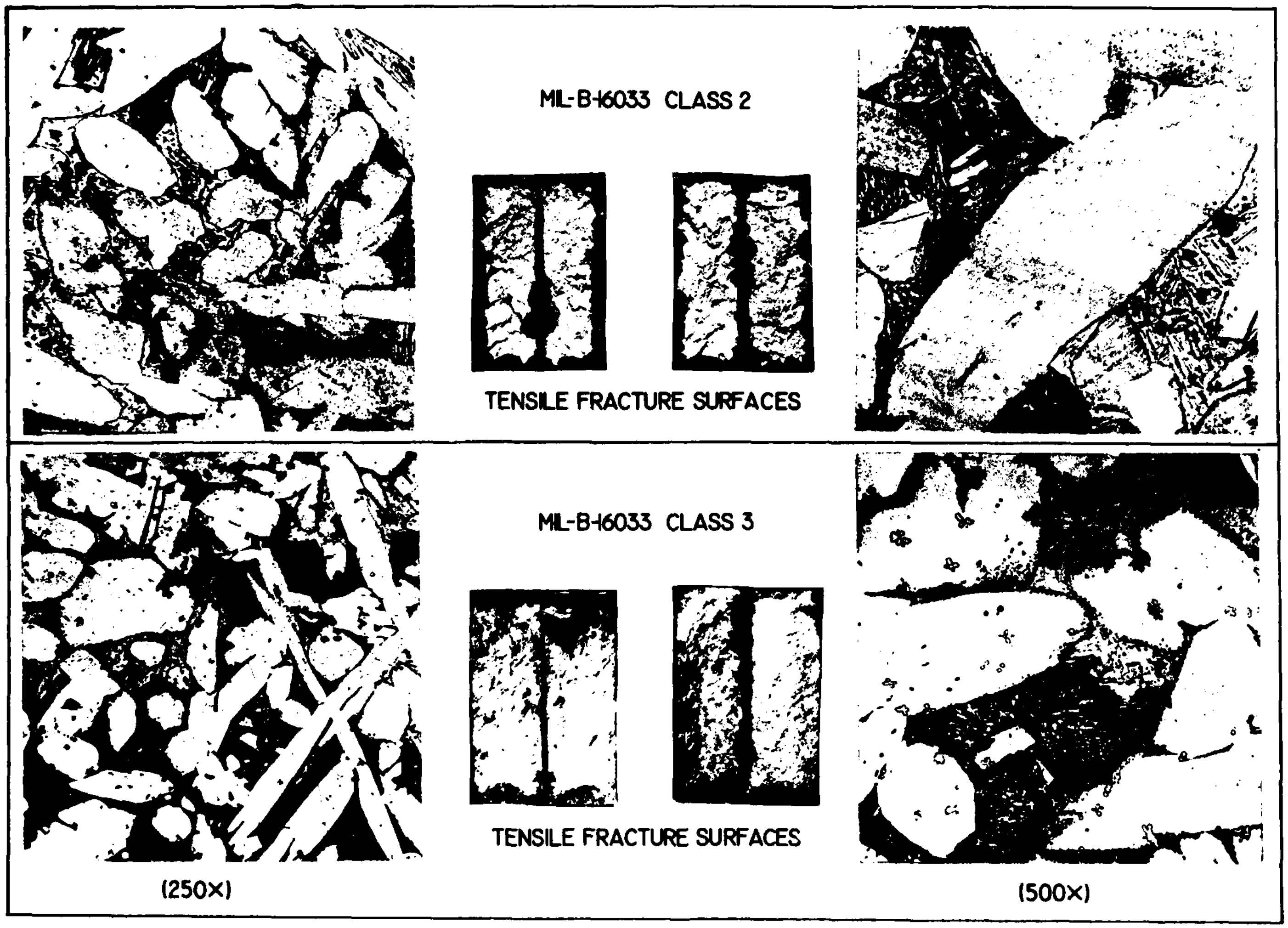

FIG. 13 DEALUMINIZATION ATTACK ON AS-CAST ALUMINUM BRONZE ALLOYS AFTER SIX MONTH SEA WATER EXPOSURE

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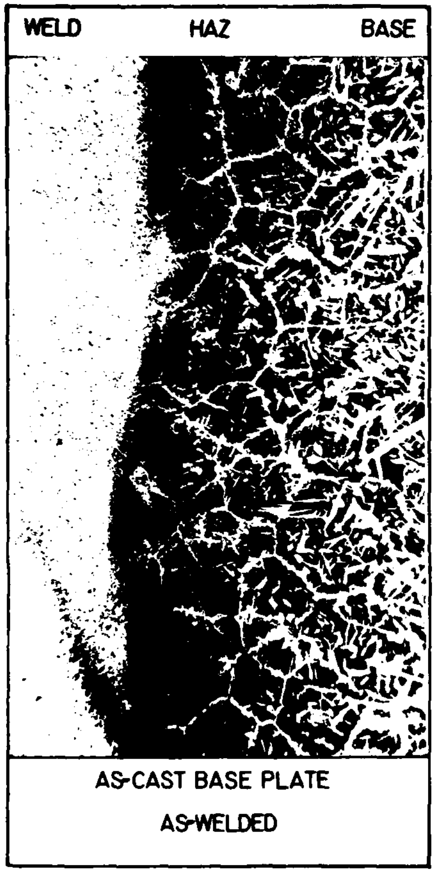

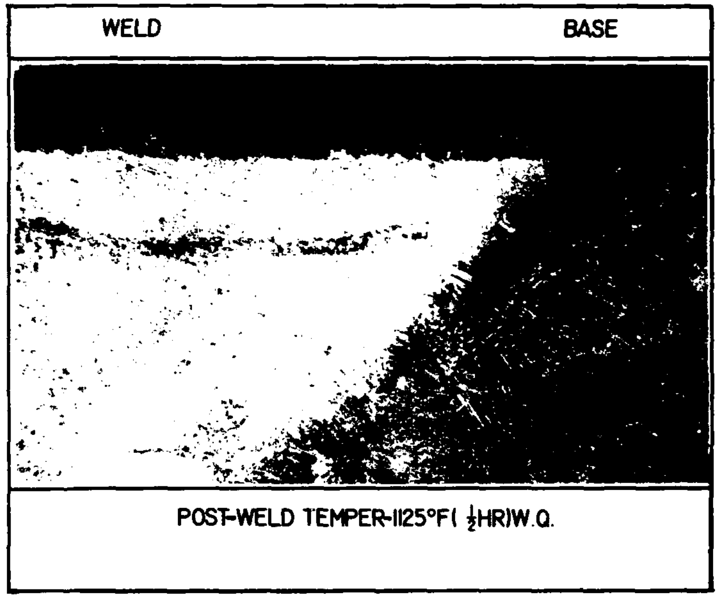

FIG. 14 PHOTOMICROGRAPHS OF WELD-BASE INTERFACE OF CLASS 4 BASE PLATE AND CODE 4 FILLER WIRE WELDMENTS AFTER SEA WATER EXPOSURE (50X)

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TABLE 1 - Chemical Analyses of Mil-B-16033 Base Metal and As-Deposited Weld Metal.

MATERIAL	COMPOSITION (Weight %)					
	Cu	Al	Fe	Ni	Mn	Sn
Class 1						
Actual	86.74	9.05	4.02	----	----	----
Specification	86.00 Min.	8.50 - 9.50	2.50 - 4.00	----	----	----
Class 2						
Actual	88.66	10.02	1.18	----	----	----
Specification	86.00 Min.	9.00 - 11.00	0.75 - 1.50	----	----	----
Class 3						
Actual	84.77	10.00	3.36	1.41	0.42	----
Specification	83.00 Min.	10.00 - 11.50	3.00 - 5.00	2.50 Max.	0.50 Max.	----
Class 4						
Actual	78.70	10.10	3.98	4.87	1.94	----
Specification	78.00 Min.	10.00 - 11.00	3.00 - 5.00	3.00 - 5.50	3.50 Max.	----
Code 3 Filler Wire						
As-Deposited	88.81	9.87	1.18	----	----	0.10
Code 4 Filler Wire						
As-Deposited	82.02	9.31	3.70	4.24	0.68	----

TABLE 2 - Tensile Properties and Fracture Appearance of Mil-B-16033 Aluminum Bronze Base Plate After Sea Water Corrosion Tests.

CONDITION OF BASE PLATE	TENSILE PROPERTIES									FRACTURE APPEARANCE	
	Yield Strength (Ksi) (1)			Tensile Strength (Ksi)			Elongation (% in 2")				
	Control	Six Months	One Year	Control	Six Months	One Year	Control	Six Months	One Year	Six Months	One Year
Class 1											
As-Cast	31.2	30.3	26.9	80.0	75.9	70.3	35.0	27.0	22.0	CLEAN	CLEAN
1125°F (1½hr) W.Q.	31.3	29.5	29.1	79.6	76.6	76.8	45.0	37.0	32.0	CLEAN	CLEAN
1625°F (2hr) W.Q. 1125°F (1½hr) W.Q.	33.4	32.2	29.8	85.8	82.6	81.3	37.0	31.5	31.0	CLEAN	CLEAN
Class 2											
As-Cast	32.9	29.3	24.2	67.6	40.2	26.6	11.0	3.5	2.5	DEALUMINIZATION	DEALUMINIZATION
1125°F (1½hr) W.Q.	29.2	29.5	31.6	76.5	70.9	70.0	19.0	15.5	13.5	DEALUMINIZATION	DEALUMINIZATION
1625°F (2hr) W.Q. 1125°F (1½hr) W.Q.	41.8	41.4	37.0	89.6	88.8	87.1	14.5	14.0	14.5	CLEAN	CLEAN
Class 3											
As-Cast	33.5	31.6	27.7	82.9	63.2	51.2	13.0	6.0	5.5	DEALUMINIZATION	DEALUMINIZATION
1125°F (1½hr) W.Q.	33.9	29.6	25.4	87.0	86.5	72.4	21.5	22.5	14.5	DEALUMINIZATION	DEALUMINIZATION
1625°F (2hr) W.Q. 1125°F (1½hr) W.Q.	46.6	47.4	49.0	99.3	103.2	99.7	15.0	22.5	18.0	CLEAN	CLEAN
Class 4											
As-Cast	48.4	49.0	47.6	92.0	88.0	74.9	6.5	5.5	3.0	CLEAN	DEALUMINIZATION
1625°F (2hr) W.Q. 1125°F (1½hr) W.Q.	79.6	77.9	75.6 (2)	115.5	113.7	108.0 (2)	5.0	4.0	3.0 (2)	CLEAN	CLEAN

SPECIFICATION (3)	Yield Strength AS-CAST	Yield Strength HEAT TREATED	Tensile Strength AS-CAST	Tensile Strength HEAT TREATED	Elongation AS-CAST	Elongation HEAT TREATED
Class 1	25.0	——	65.0	——	20.0	——
Class 2	25.0	40.0	65.0	80.0	20.0	12.0
Class 3	30.0	45.0	75.0	90.0	12.0	6.0
Class 4	40.0	60.0	90.0	110.0	6.0	5.0

(1) 0.005 inches per inch extension under load
(2) One determination
(3) Mil-B-16033, minimum

TABLE 3 - Tensile Properties, Fracture Location and Appearance of Mil-B-16033 Al-Bronze Weldments After Sea Water Corrosion Tests.

CONDITION OF BASE PLATE	TENSILE PROPERTIES									FRACTURE LOCATION AND APPEARANCE		
	Yield Strength (1) (Ksi)			Tensile Strength (Ksi)			Elongation (% in 2")					
	Control	Six Months	One Year	Control	Six Months	One Year	Control	Six Months	One Year	Control	Six Months	One Year
Class 1 - Code 3												
As-Cast	33.7	33.9	17.3 (3)	80.5	77.5	19.9	33.0	26.0	1.0	BASE	BASE (CLEAN)	HAZ WELD (DEAL) (4)
1625°F(2hr)W.Q. 1125°F(1½hr)W.Q.	35.5	35.4	24.9 (3)	86.0	70.2	22.5	32.0	17.0	1.0	BASE	WELD (DEAL)	HAZ WELD (DEAL)
Post Weld Temper (2)	35.2	34.7	29.9	84.0	81.9	72.9	34.0	31.0	20.0	BASE	BASE WELD (CLEAN)	HAZ WELD (DEAL)
Class 2 - Code 3												
As-Cast	36.9	36.6	(5)	72.0	40.1	23.2	10.5	5.0	2.0	BASE	BASE (DEAL)	BASE (DEAL)
1625°F(2hr)W.Q. 1125°F(1½hr)W.Q.	42.4	38.1	31.5	80.1	72.9	40.8	9.5	10.0	1.5	BASE	BASE HAZ (DEAL)	HAZ WELD (DEAL)
Post Weld Temper	40.5	37.9	36.3	84.4	77.3	74.0	15.0	13.0	12.0	BASE	BASE (CLEAN)	BASE WELD (DEAL)
Class 3 - Code 3												
As-Cast	38.3	40.5	31.3	85.1	63.0	49.1	14.5	8.0	5.0	BASE	BASE (DEAL)	BASE (DEAL)
1625°F(2hr)W.Q. 1125°F(1½ hr)W.Q.	44.5	43.2	41.7	98.0	94.8	61.4	15.5	13.5	5.0	BASE	WELD (DEAL)	WELD (DEAL)
Post Weld Temper	44.3	45.2	40.4	96.1	98.2	87.8	18.5	24.0	12.5	BASE	BASE (CLEAN)	HAZ (DEAL)
Class 4 - Code 3												
As-Cast	49.9	45.0	33.1	87.0	75.9	41.4	4.0	4.0	1.0	WELD	WELD (DEAL)	HAZ (DEAL)
1625°F(2hr)W.Q. 1125°F(1½hr)W.Q.	48.7	51.4	50.9	98.4	96.2	68.4	4.5	4.0	2.0	WELD	WELD (CLEAN)	HAZ (DEAL)
Post Weld Temper	52.5	51.1	52.0	101.6	96.7	97.6	7.0	6.0	7.5	WELD	WELD (CLEAN)	WELD (DEAL)
Class 4 - Code 4												
As-Cast	61.3	58.6	(5)	93.6	75.3	38.3	4.5	2.5	0.0	WELD	WELD (DEAL)	HAZ (DEAL)
1625°F(2hr)W.Q. 1125°F(1½hr)W.Q.	69.4	64.6	67.6 (3)	105.5	105.9	59.1	3.0	3.0	1.0	WELD	WELD (CLEAN)	HAZ (DEAL)
Post Weld Temper	71.3	72.6	67.6 (3)	112.5	112.2	101.1 (3)	5.0	5.0	3.0 (3)	WELD	BASE (CLEAN)	BASE (DEAL)

(1) 0.005 inches per inch extension under load
(2) 1125°F(1½ hr)W.Q. after welding on "Heat Treated" base plate
(3) One determination
(4) DEAL - Dealuminization
(5) No yielding observed

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13. ABSTRACT

Effects of microstructure, heat treatment and welding on the corrosion (dealuminization) resistance of cast aluminum bronzes (MIL-B-16033) after six months and one year exposure to flowing sea water are described. Results show that the bronzes are both composition and structure sensitive to corrosion attack. Heat treatment either eliminates of minimizes dealuminization attack; however, welding nullifies any advantages derived from heat treatment. Post-weld treatment can restore corrosion resistance provided proper filler materials are used.

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POST-WELD TEMPER						
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2. Bronze castings-Heat treatment
3. Bronze castings-Welding

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III. Crisci, J. R.
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